MATLAB BASED MODELING OF PHOTOVOLTAIC ARRAY CHARACTERISTICS

A THESIS IN PARTIAL FULFILMENTS OF REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF
Bachelor of Technology

in

Electrical Engineering

By

Bibek Mishra
(108EE010)

Bibhu Prasanna Kar
(108EE027)

Department of Electrical Engineering
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Under the supervision of

PROF. BIDYADHAR SUBUDHI

Department of Electrical Engineering
National Institute of Technology, Rourkela

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NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the Project entitled **"MATLAB BASED MODELING OF PHOTOVOLTAIC ARRAY CHARACTERISTICS"** submitted by Bibek Mishra(108EE010) and Bibhu Prasanna Kar(108EE027) in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at National Institute of Technology, Rourkela (Deemed University), is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date: (Prof. Bidyadhar Subudhi)

Place: Rourkela Department of Electrical Engineering

NIT, Rourkela

ACKNOWLEDGEMENT

We would like to express our gratitude towards all the people who have imparted their valued time and efforts to help us in completing this project, without whom it would not have been possible for us to understand and examine the project.

We would like to thank **Prof. Bidyadhar Subudhi**, Professor and Head, Department of Electrical Engineering, our Project Supervisor, for his guidance, support, motivation and encouragement throughout the period this work was carried out. His readiness and eagerness for consultation at all times, his educative inputs, his concern and assistance have been invaluable.

Bibek Mishra(108EE010)

Bibhu Prasanna Kar(108EE027)

ABSTRACT

Solar energy, radiant light and heat from the sun, has been reined by humans since ancient times using a range of ever-evolving technologies. Solar radiant energy accounts for most of the usable renewable energy on earth. Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. In this thesis, the PV array is modeled and its voltage-current characteristics and power-voltage characteristics are simulated and optimized. The main encumbrance for the reach of Photovoltaic systems is their low efficiency and high capital cost. Here we intend to examine a schematic to draw out maximum obtainable solar power from a PV module for use in a DC application. The concept of Maximum Power Point Tracking is to be implemented which results in appreciable increase in the efficiency of the Photovoltaic System. Different schemes of MPPT algorithms such as Perturb and Observe, Incremental Conductance, Fractional Open Circuit Voltage, Fractional Short Circuit Current, Fuzzy Logic Control, Neural Network are to be studied and implemented. The MPPT algorithm thus proposed will identify the suitable duty ratio in which the DC/DC converter should be operated to obtain maximum power output.

CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION:

The energy which is harvested from the natural resources like sunlight, wind, tides, geothermal heat etc. is called Renewable Energy. As these resources can be naturally replenished, for all practical purposes, these can be considered to be limitless unlike the tapering conventional fossil fuels. The global energy crunch has provided a renewed impulsion to the growth and development of Clean and Renewable Energy sources. Clean Development Mechanisms (CDMs) [1] are being adopted by organizations all across the globe. Another advantage of utilizing renewable resources over conventional methods is the significant reduction in the level of pollution associated.

The cost of conventional energy is rising and solar energy has emerged to be a promising alternative. They are abundant, pollution free, distributed throughout the earth and recyclable. PV arrays consist of parallel and series combination of PV cells that are used to generate electrical power depending upon the atmospheric specifies (e.g. solar insolation and temperature).

1.2 HISTORICAL DEVELOPMENT:

Photovoltaic technology in reality goes back over 160 years. The basic science was first came upon in 1839 but the pace of advancement really hastened in two major drives in the 20th century.

Bell Laboratories, discovered silicon had photoelectric attributes and quickly developed Si solar cells, achieving 6% efficiency and former satellites were the elemental use for these first solar cells. To spur acceptance, Germany and then Japan initiated appreciable subsidy programs and now those markets exist largely without grants. In 2007, California leads the US with a similar 10-year program.

1.3 APPLICATION:

Solar technologies are broadly qualified as either passive or active depending on the way they catch, change over and distribute sunlight. Active solar proficiencies use photovoltaic arrays, pumps, and fans to convert sunlight into executable outputs. Passive solar techniques include selecting materials with favorable thermal attributes, and citing the position of a building to the Sun. The standalone PV Systems have been used for solar street lighting, home lighting system, SPV water pumping system. A hybrid system installed with a backup system of diesel generator can be used in remote military installations, health centres and tourist bungalows. In grid connected system the major part of the load during the day is supplied by the PV array and then from the grid when the sunlight is not sufficient.

1.4 WORK SUMMARY :

Different forms of renewable energies have been discussed along with the most important one, the solar energy. The concepts of a PV cell and its characteristics have been studied and obtained through its characteristic equation. Boost converter has been studied under both open loop and closed loop conditions. The P-V, I-V, P-I curves have been obtained at varying irradiation levels and temperatures. Effects of partial shading on the Photovoltaic array have been demonstrated with the variations in the characteristics under these conditions. An MPPT model has been designed to extract maximum power from the photovoltaic array.

1.5 Different sources of Renewable Energy:

I. **Wind Power**:

Worldwide there are now many thousands of wind turbines functioning, with a total nameplate capability of 194,400MW.The wind turbines range from around 600 kW to 5 MW [2] of rated power. The power output increases rapidly with an increase in available wind velocity as the former.

II. **Solar power**:

This can be employed in two major ways. The captured heat can be used as solar thermal energy with important applications in space heating. On the other hand it can also be converted into the most useful form of energy, the electrical energy. The latter can be achieved with the use of solar photovoltaic cell [3].

III. **Biomass**:

Biomass works as a natural battery to store the sun's energy and yield it on requirement. Biomass energy is derived from five distinct energy sources; garbage, wood, landfill gases, waste, and alcohol fuels. This way, biomass works as a natural battery to store the sun's energy [4] and yield it on requirement.

IV. **Geothermal**:

Geothermal energy is the thermal energy which is generated and stored [5] within the layers of the Earth. The gradient thus developed brings about an uninterrupted conduction of heat from the core to the surface of the earth. This gradient can be applied to heat water to produce superheated steam and use it to run steam turbines to generate electricity. The primary failing of geothermal energy is that it is usually limited to regions near tectonic plate boundaries, though recent progresses have led to the multiplication of this technology [6].

In tropic countries like India and other places where solar energy is available in plenty, photovoltaic has emerged as a major candidate for meeting the energy demand. It extends an alternative for clean (pollution free) energy source, with about no running and sustainment cost.

Chapter 2
Literature Review

A maximum power point tracking algorithm is absolutely necessary to increase the efficiency of the solar panel as it has been found that only 30-40% of energy incident is converted into electrical energy. Among all the MPPT methods, Perturb & Observe (P&O) and Incremental Conductance are most commonly used because of their simple implementation and lesser time to track the maximum power point and also other economic reasons.

Under suddenly changing weather conditions (irradiation level) as MPP changes continuously, P&O takes it as a change in MPP due to perturbation rather than that of irradiation and sometimes ends up in calculating wrong MPP[7]. However this problem is eliminated in Incremental Conductance method as the algorithm takes two samples of voltage and current to compute MPP. However, instead of more efficiency the complexity of the algorithm is very high compared to the former one and hence the cost of execution increases. So we have to extenuate with a trade-off between ramification and efficiency.

It has been observed that the efficiency of the system also relies upon the converter. Generally, it is maximum for a buck analysis, then for buck-boost analysis and minimum for a boost analysis. When multiple solar modules are connected in parallel, another analog technique TEODI is also very efficient which operates on the principle of equalization of output operating points in correspondence to force displacement of input operating points of the identical operating system. It is very elementary to carry out and has high efficiency both under stationary and time varying atmospheric conditions [8]

CHAPTER 3

CHARACTERISTICS OF SOLAR ARRAY

A photovoltaic system uses one or more solar modules or panels to convert solar energy to electrical energy. Basically, its components include solar panels, mechanical and electrical connections and means of modifying the electrical output we get.

3.1 PHOTOVOLTAIC CELL:

Solar cells are the building blocks of a PV array. These are made up of semiconductor materials like silicon etc. A thin semiconductor wafer is specially treated to form an electric field, positive on a side and negative on the other. Electrons are knocked loose from the atoms of the semiconductor material when light strikes upon them. If an electrical circuit is made attaching a conductor to the both sides of the semiconductor, electrons flow will start causing an electric current. It can be circular or square in construction.

3.2 PHOTOVOLTAIC MODULE:

The voltage generated by a single solar cell is very low, around 0.5V. So, a number of solar cells are connected in both series and parallel connections to achieve the desired output. In case of partial shading, diodes may be needed to avoid reverse current in the array. Good ventilation behind the solar panels are provided to avoid the possibility of less efficiency at high temperatures.

3.3 PHOTOVOLTAIC ARRAY:

Again the power produced by a single module is not sufficient to meet the power demands for most of the practical purposes. PV arrays can use inverters to convert the dc output into ac and use it for motors, lighting and other loads. The modules are connected in series for more voltage rating and then in parallel to meet the current specifications.

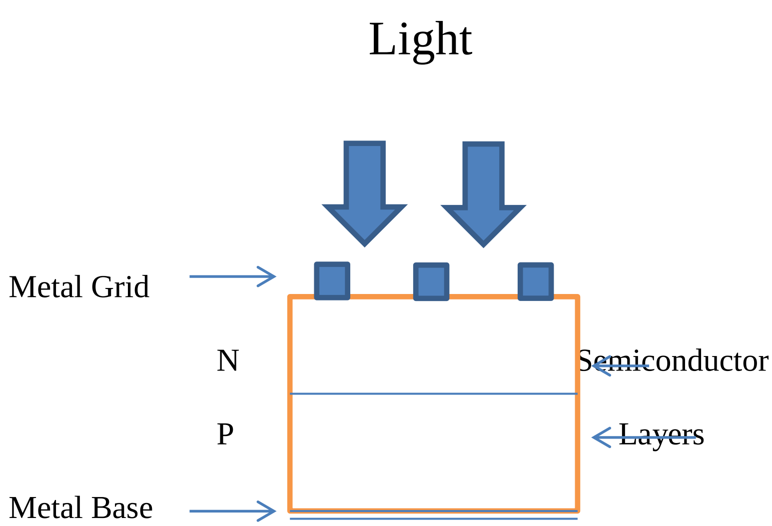

Fig. 1: Structure of a PV cell

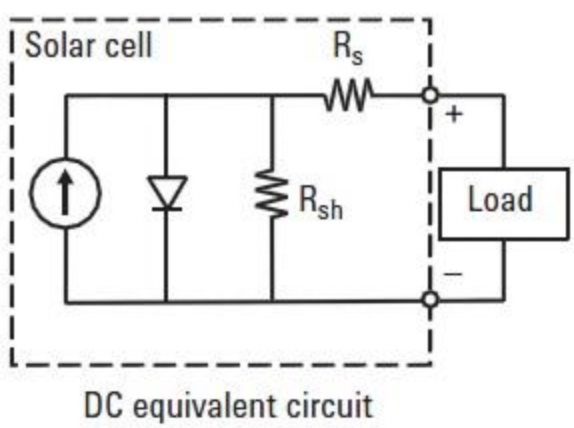

Fig. 2: Simplified circuit diagram of a solar PV cell

The photovoltaic cell output voltage is basically a function of the photocurrent which is mainly determined by load current depending on the solar irradiation level during the operation.

$$V_c = (A*k*Tc/e)\ln((I_{ph}+I_0-I_c)/I_0) - R_s*I_c$$

The symbols used are

V_c: cell output voltage, V.

T_c: reference cell operating temperature (20 °C).

R_s: series resistance of cell (0.001 Ω).

I_{ph}: photocurrent, function of irradiation level and junction temperature (5 A).

I_0: reverse saturation current of the diode ($2*10^{-4}$ A).

I_c: cell output current, A.

k: Boltzmann constant (1.38 × 10-23 J/K).

e: electron charge (1.602 × 10^-19 C).

For accurate modeling of the solar panel, two diode circuit could have been used. But our scope of study is limited to single diode model. Following are the ideal characteristics of a solar array which show the variation of current and voltage with respect to voltage. [13]

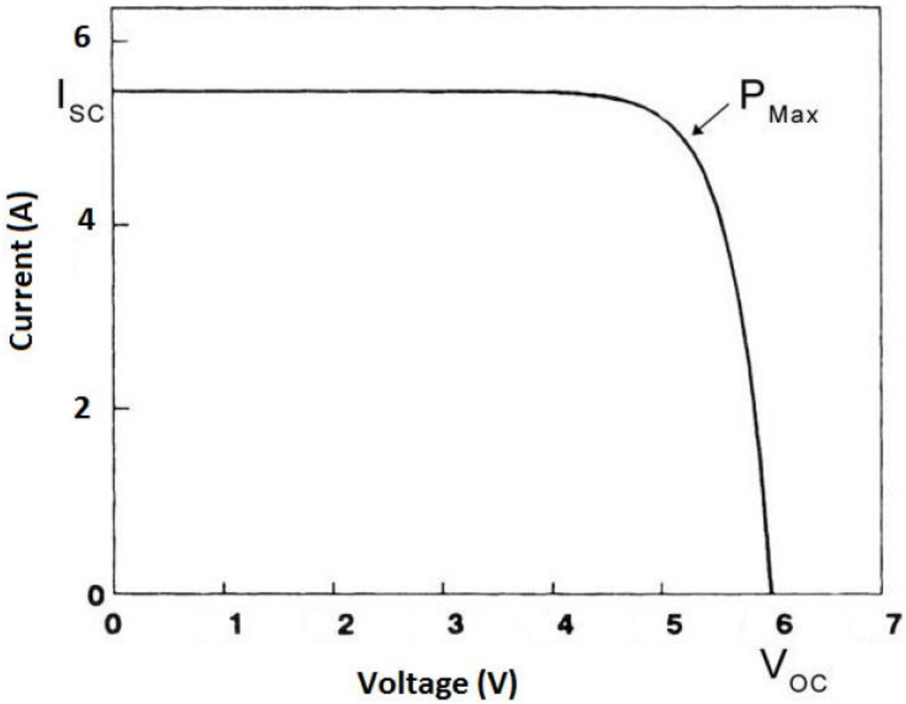

Fig. 3: Typical I-V characteristics of a solar panel

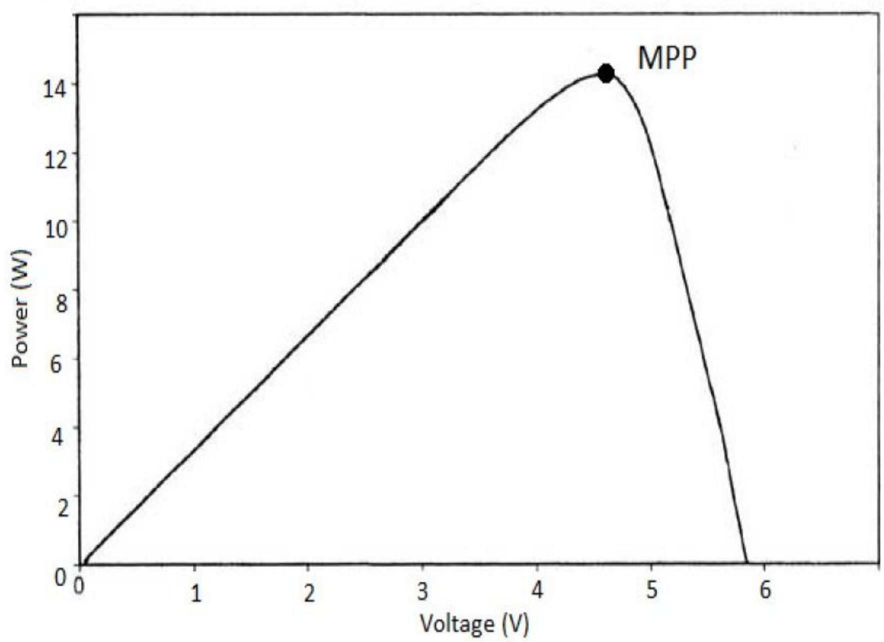

Fig. 4: Typical P-V characteristics of solar panel [9]

SIMULATION OF PV ARRAY IN MATLAB[9]

```
T=28+273;
Tr1=40; % Reference temperature in degree Fahrenheit
Tr=((Tr1-32))+273; % Reference temperature in kelvin
S=[100 80 60 40 20]; % Solar radiation in mW/sq.cm
%S=70;
ki=0.00023; % in A/K
Iscr=3.75; % SC Current at ref. temp. in A
Irr=0.000021; % in A
k=1.38065*10^(-23); % Boltzmann constant
q=1.6022*10^(-19); % charge of an electron
A=2.15;
Eg0=1.166;
alpha=0.473;
beta=636;
Eg=Eg0-(alpha*T*T)/ (T+beta)*q; % band gap energy of semiconductor used
cell in joules
Np=4;
Ns=60;
V0=[0:1:300];
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis([0 50 0 20]);
xlabel('Voltage in volt');
ylabel('Current in amp');
hold on;
figure(2)
plot(V0,P0);
axis([0 50 0 400]);
xlabel('Voltage in volt');
ylabel('Power in watt');
hold on;
figure(3)
plot(I0,P0);
axis([0 20 0 400]);
xlabel('Current in amp');
ylabel('Power in watt');
hold on;
end
end
```

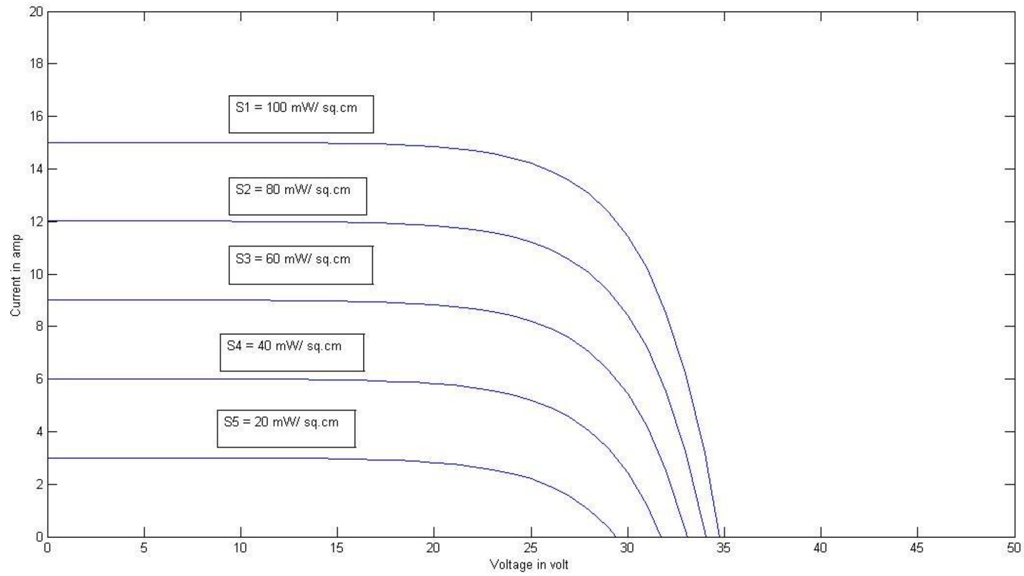

Fig 5: I-V characteristics for different insolation values

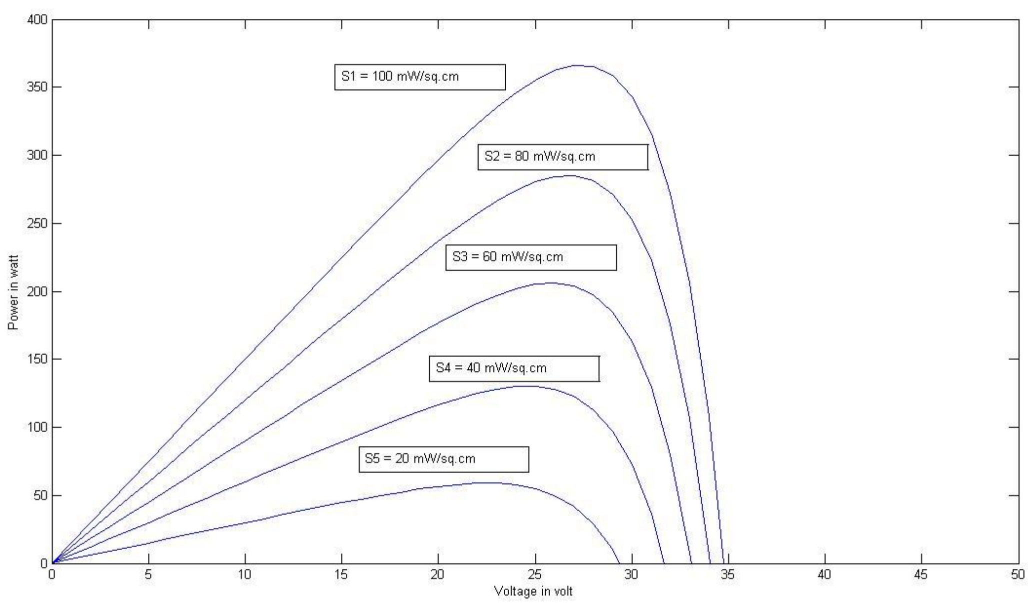

Fig 6: P-V characteristics for different insolation values

PV ARRAY SIMULINK MODEL

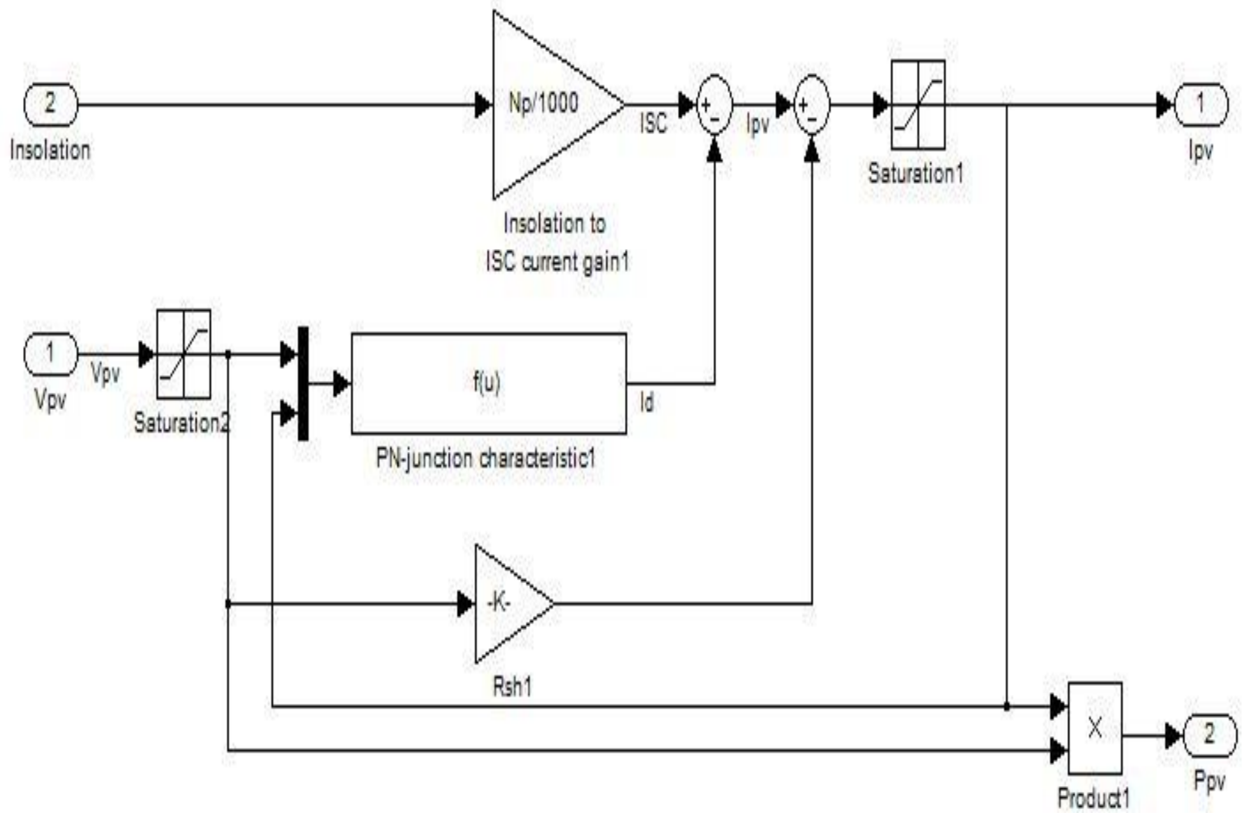

Fig 7: SIMULINK model of photovoltaic array

CHAPTER 4

BOOST CONVERTER

The maximum power point tracking is essentially a load matching problem. A DC to DC converter is required for changing the input resistance of the panel to match the load resistance by varying the duty cycle.

There are four topologies for the DC to DC regulators: boost converter, buck converter, buck-boost converter, cứk converter. Since our project work deals with the boost converter, further discussions will be centered on this one.

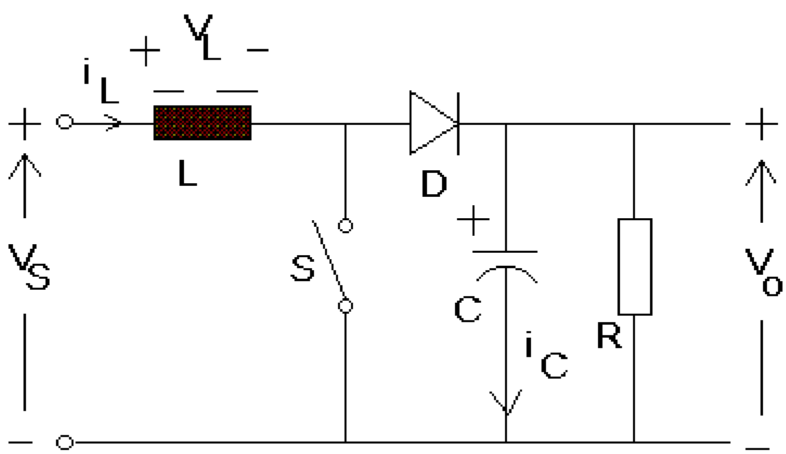

Fig. 8: Boost Converter Circuit Diagram

Mode 1 Operation of Boost Converter:

When the switch is closed the inductor is charged through the battery and stocks the energy. In this mode, inductor current increases exponentially but for ease we assume that the charging and the discharging of the inductor are linear. The diode blocks the flow of current and so the load current remains constant which is being supplied due to the discharging of the capacitor.

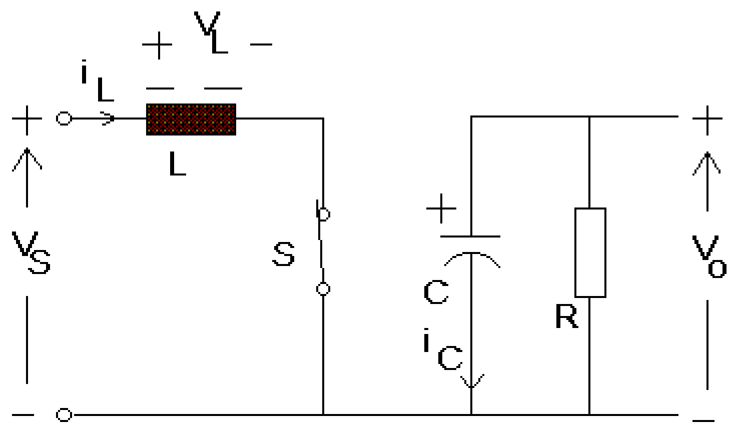

Fig. 9: Mode 1 Operation

Mode 2 Operation of Boost Converter:

In mode 2 the switch is open and so the diode becomes short circuited. The energy stored in the inductor gets discharged through opposite polarities which charge the capacitor. The load current remains constant throughout the operation.

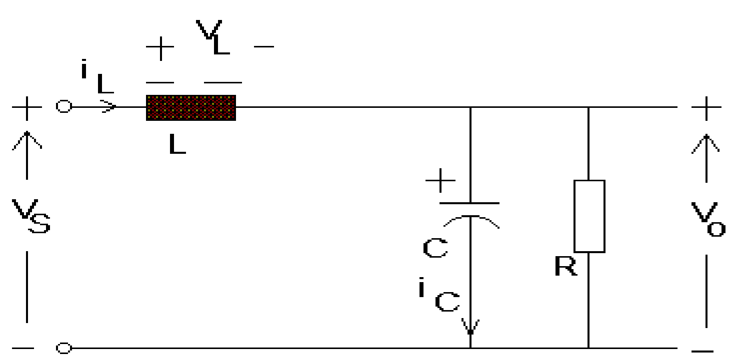

Fig. 10: Mode 2 Operation[10]

CALCULATION OF CIRCUIT PARAMETERS:

Inductance L=k(1-k)R/2*f

Capacitance=k/2*f*R

Where, k=duty cycle

R=resistance

f=1/T=switching frequency

Converter Parameter	Value
Inductance(L)	80 uH
Inductor Resistance(R_L)	80 m ohm
Capacitance(C)	1.68 uF
Capacitor Resistance(R_C)	5 m ohm
Switching Frequency(f_S)	100 KHz
Gate Voltage(V_G)	5V
Duty Ratio(D)	0.61
Load Resistance(R)	120 ohm
Output Voltage(V_O)	12V

Boost Converter Simulation (24 to 48V):

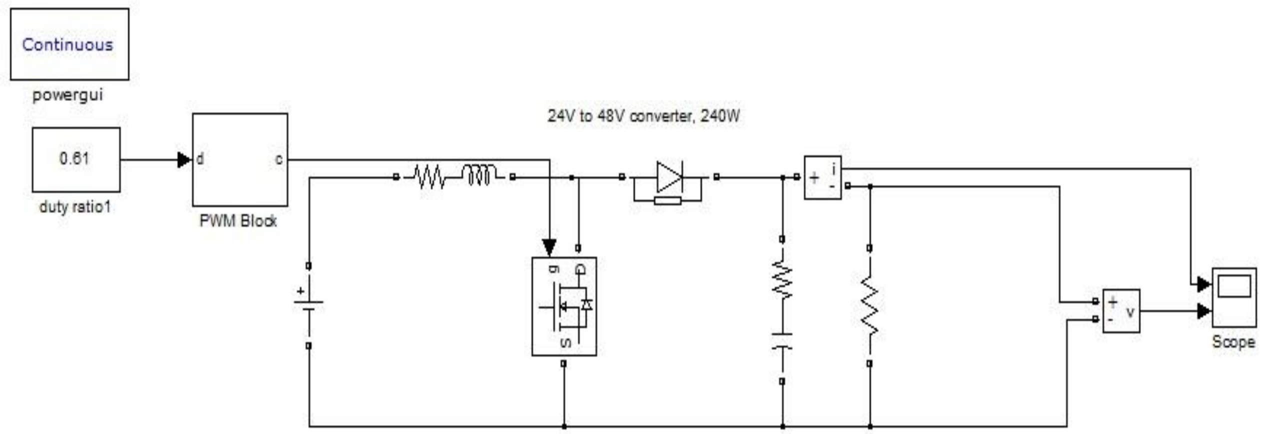

Fig 11: Open Loop Boost Converter

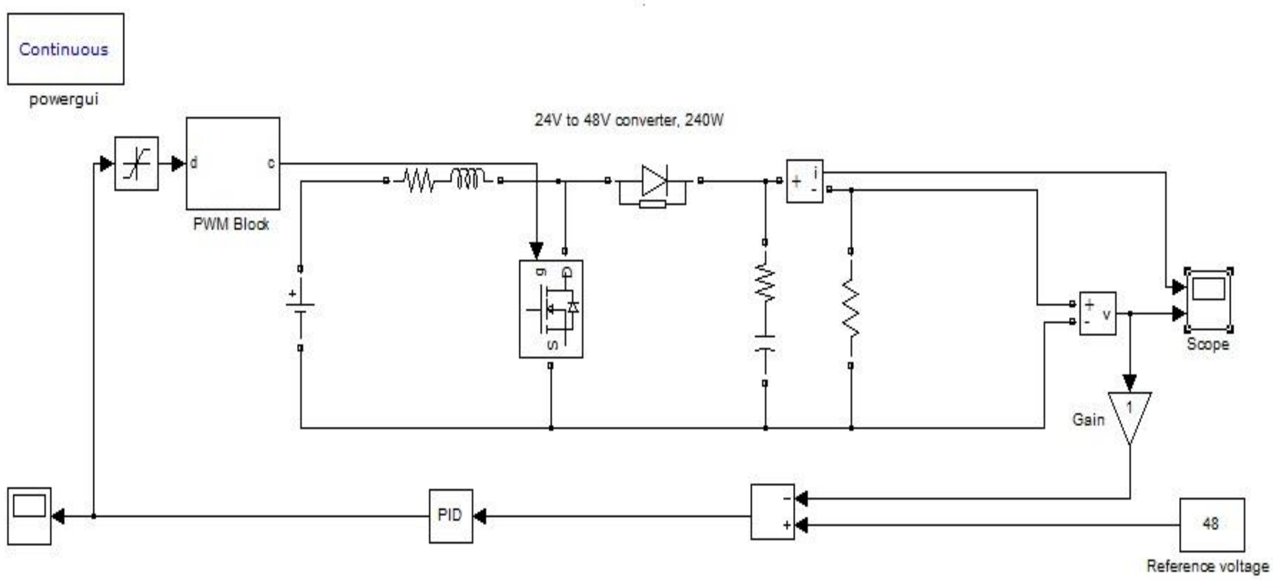

Fig 12: Closed Loop Boost Converter

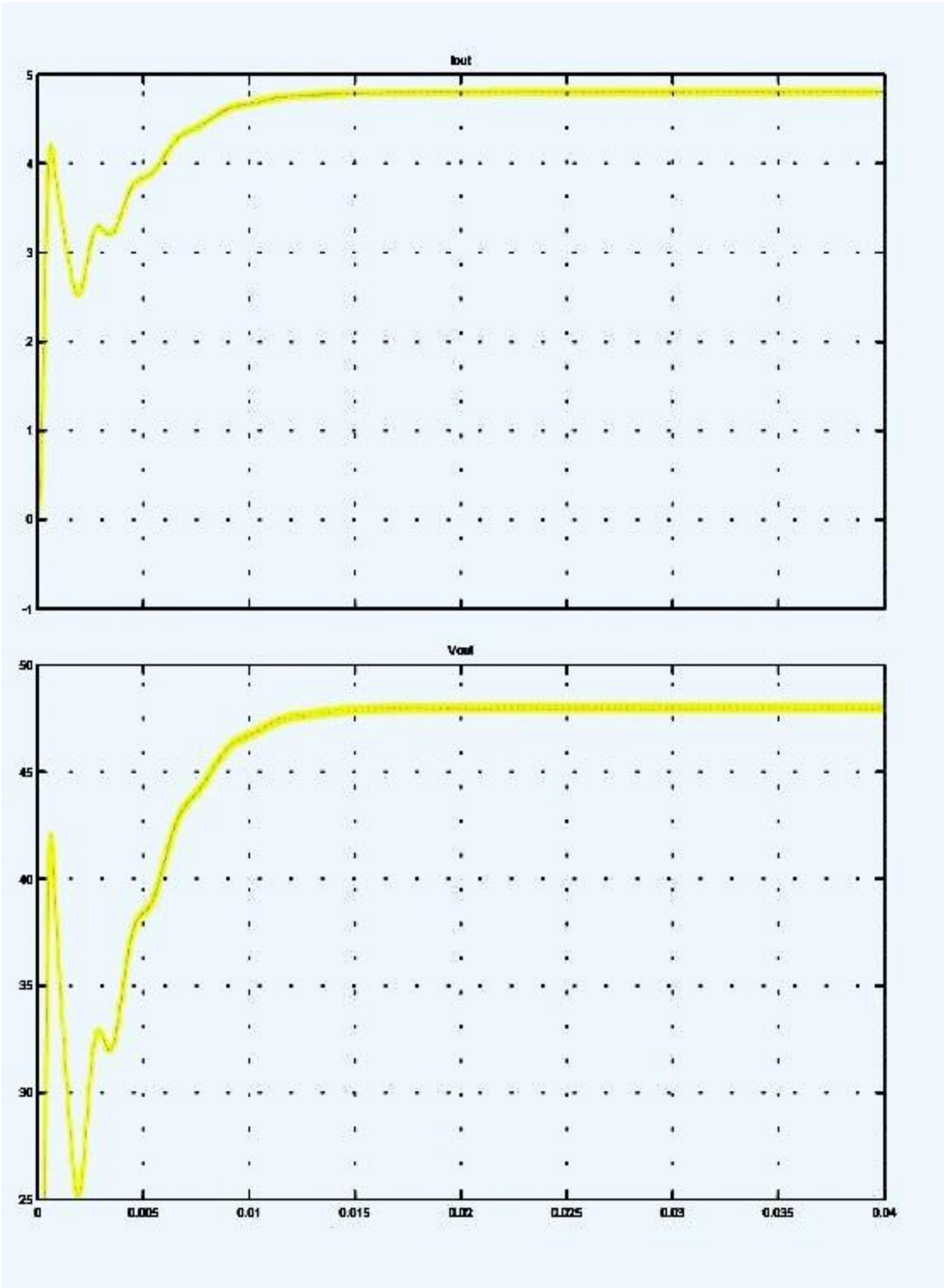

Fig. 13: Open loop control characteristics of Boost Converter (48V output)

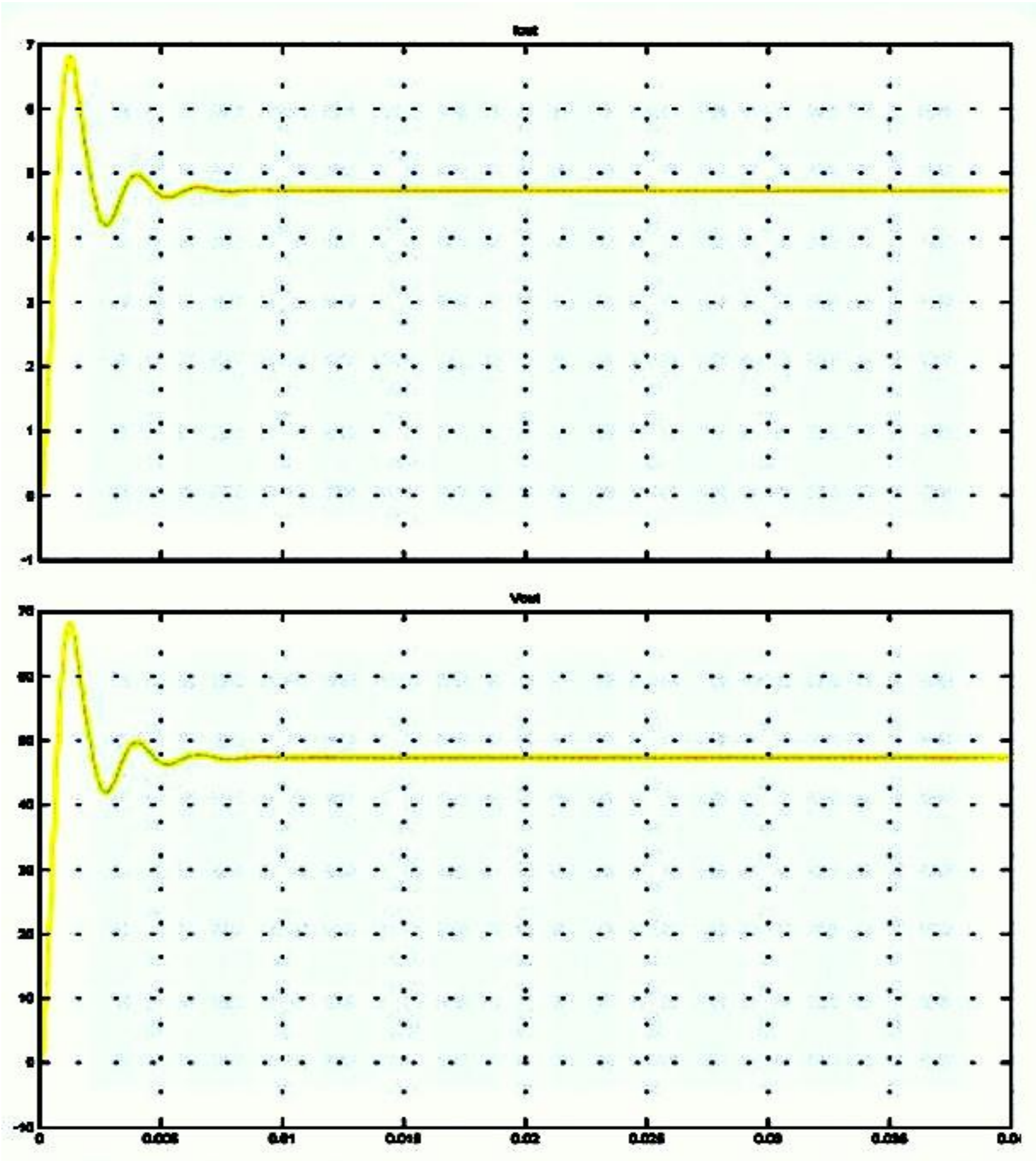

Fig. 14: Closed loop control characteristics of Boost Converter (48V output)

CHAPTER 5

Effects of Partial Shading on PV Array Characteristics

The functioning of a photovoltaic array is impacted by temperature, solar irradiance, shading, and array configuration. Frequently, the PV arrays get shadowed, wholly or partially, by the moving clouds, adjacent buildings and towers, trees, utility and telephone poles. The situation is of especial interest in case of big PV installations such as those used in distributed power generation systems. Under partly shaded conditions, the photovoltaic characteristics get more complex with more than one peaks. Yet, it is very crucial to understand and predict them in order to draw out the maximum possible power. Here, we present a MATLAB-based modeling and simulation scheme desirable for studying the I-V and P–V characteristics of a photovoltaic array under a non- inhomogeneous insolation due to partial shading. It can also be used for acquiring and assessing new maximum power point tracking methods, especially for partially shaded conditions. It can also be used as a means to study the effects of shading patterns on PV panels having dissimilar forms. It is followed that, for a set number of PV modules, the array configuration (refers to the number of series and parallel connections) importantly bears on the maximum usable power under partially shaded conditions. This is another view to which the acquired model can be applied. [12]

SIMULATION OF PV ARRAY IN MATLAB[R]

```
T=28+273;
Tr1=40; % Reference temperature in degree Fahrenheit
Tr=((Tr1-32))+273; % Reference temperature in kelvin
S= [100 20]; % Solar radiation in mW/sq.cm
%S=70;
ki=0.00023; % in A/K
Iscr=3.75; % SC Current at ref. temp. in A
Irr=0.000021; % in A
k=1.38065*10^(-23); % Boltzmann constant
q=1.6022*10^(-19); % charge of an electron
A=2.15;
Eg0=1.166;
alpha=0.473;
beta=636;
Eg=Eg0-(alpha*T*T)/ (T+beta)*q; % band gap energy of semiconductor used
cell in joules
Np=1;
Ns=36;
V0=[0:1:300];
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis ([0 25 0 5]);
xlabel('Voltage in volt');
ylabel('Current in amp');
hold on;
figure(2)
plot(V0,P0);
axis ([0 25 0 100]);
xlabel('Voltage in volt');
ylabel('Power in watt');
hold on;
figure(3)
plot(I0,P0);
axis ([0 5 0 100]);
xlabel('Current in amp');
ylabel('Power in watt');
hold on;
end
end
```

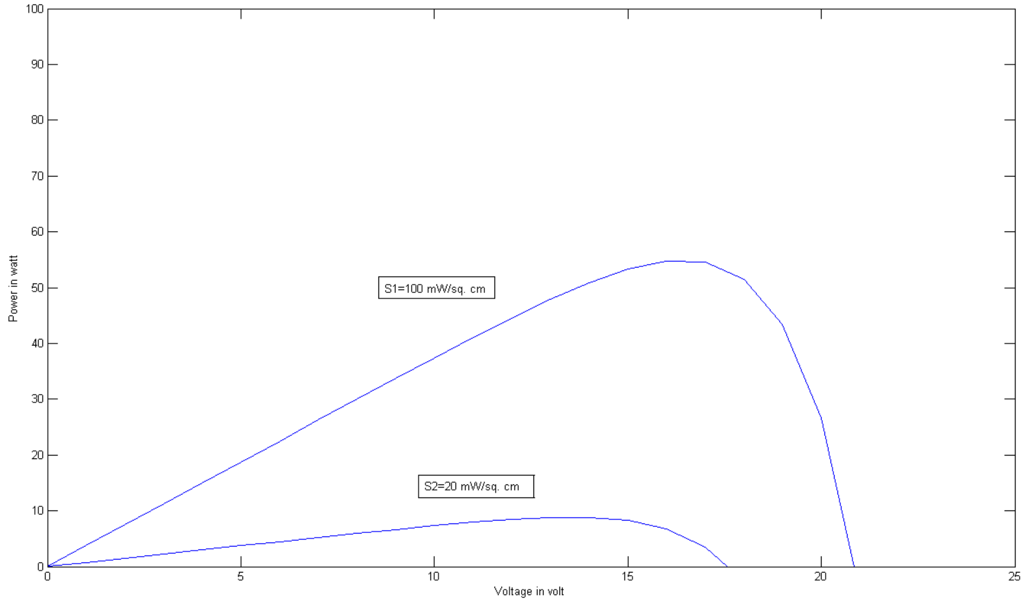

Fig 15:Effect of partial shading on PV characteristics of a single PV module

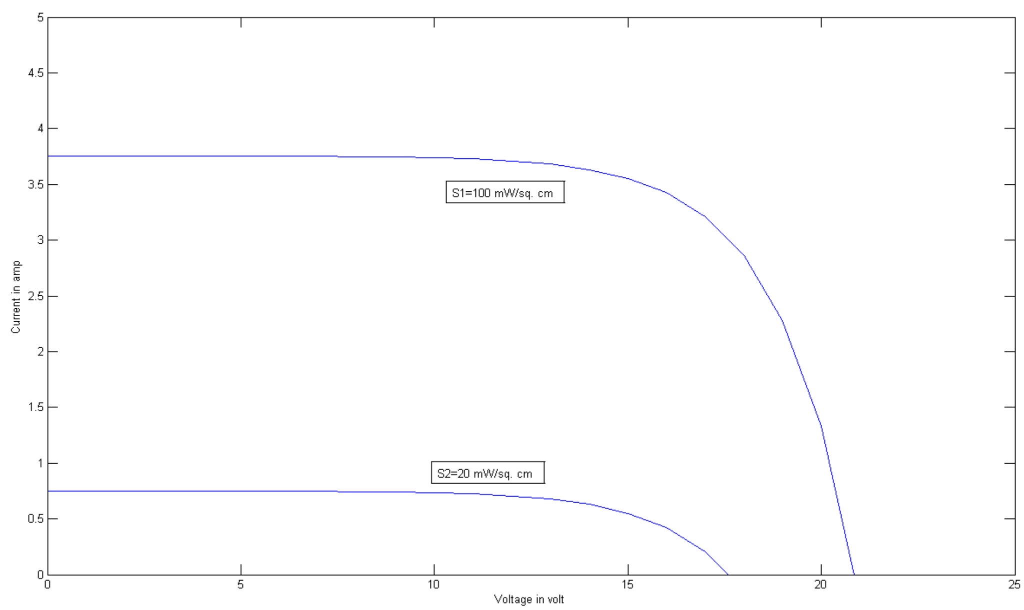

Fig 16:Effect of partial shading on IV characteristics of a single PV module

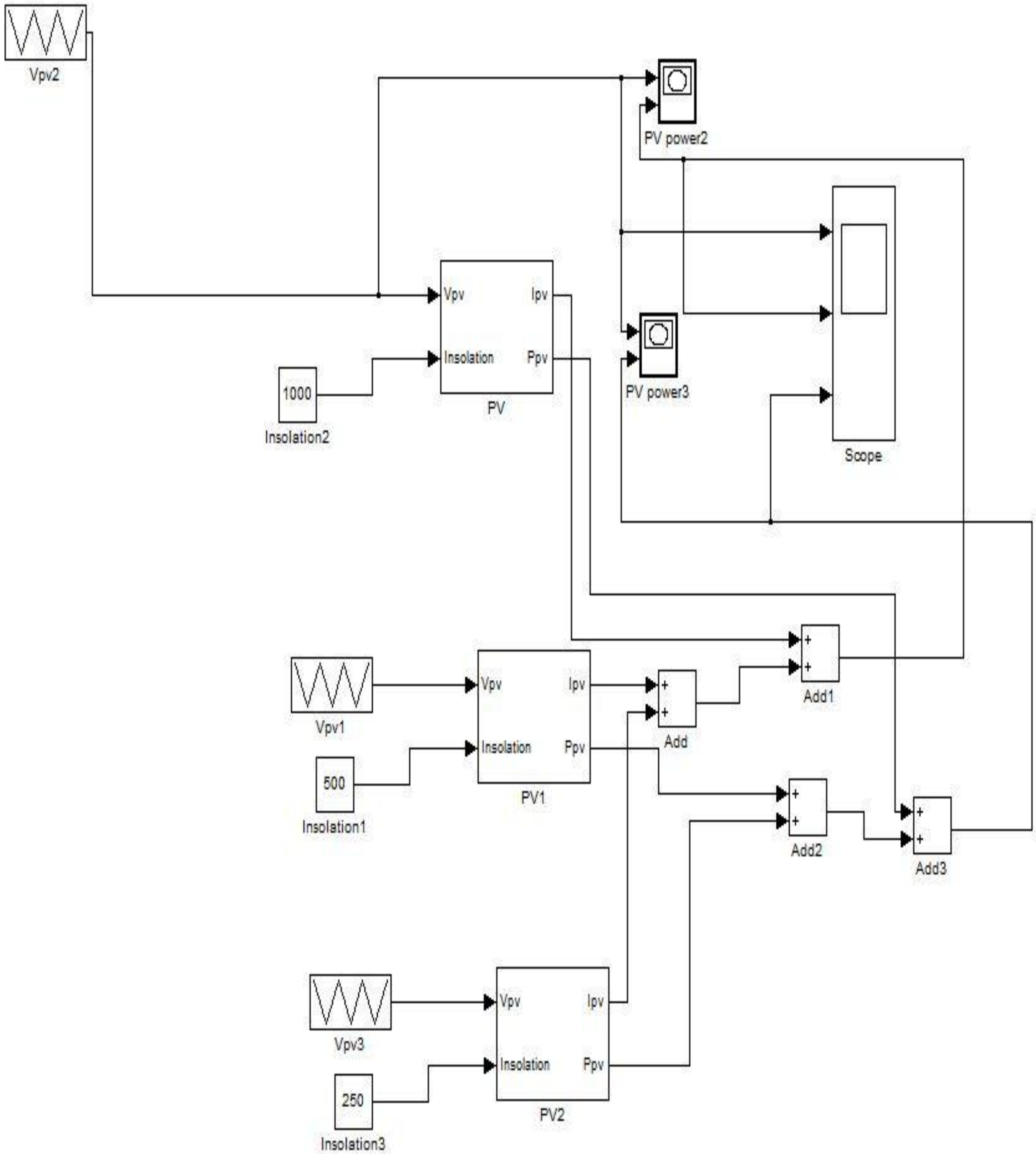

Fig 17: Simulink model for partial shading of pv array

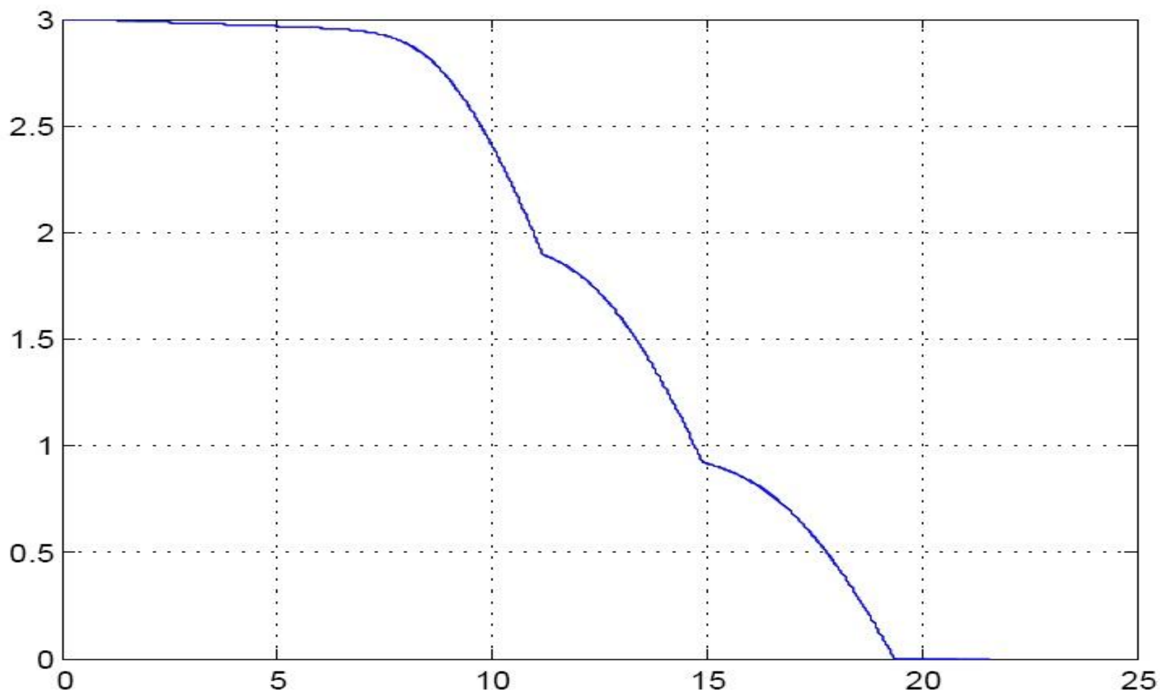

Fig 18: I-V characteristic of pv array under partial shading condition

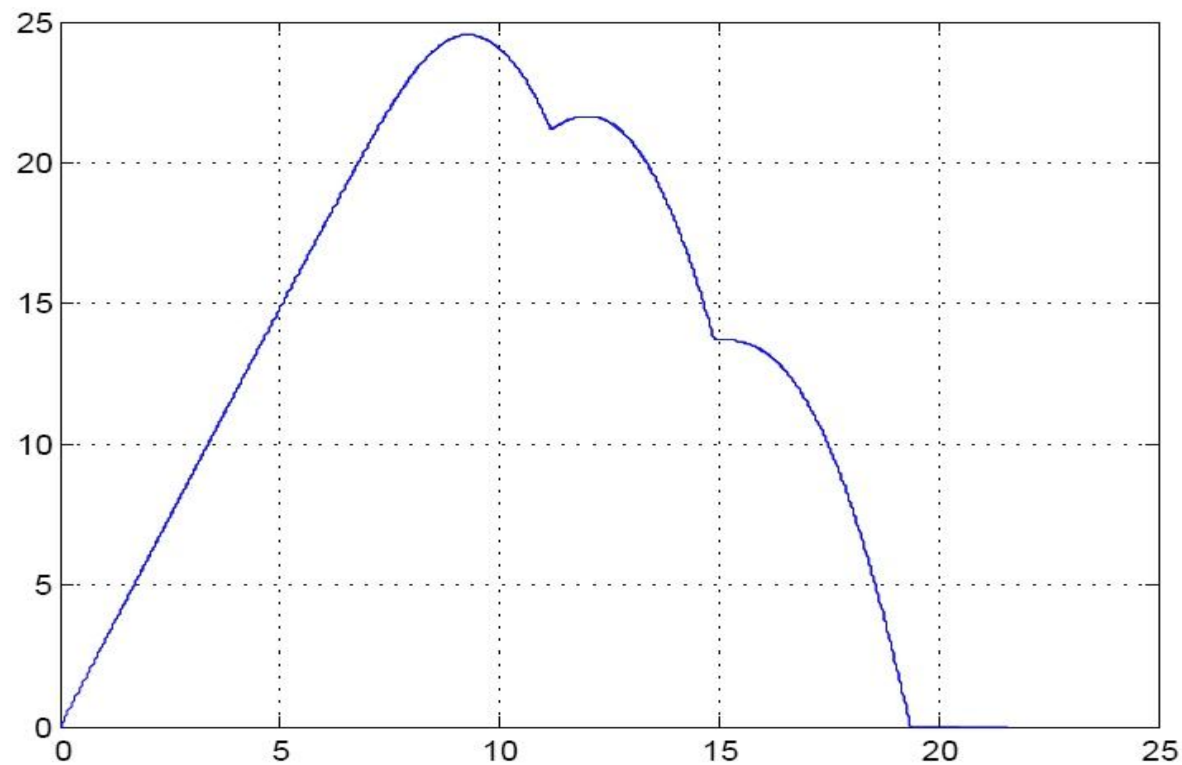

Fig 19: P-V characteristic of PV array under partial shading condition

CHAPTER 6

MPPT ALGORITHMS

MPPT ALGORITHMS

The three main versions of the hill climbing algorithm are P&O, MP&O and EPP.P&O has been described below.

Perturb and Observe

In this algorithm a slight perturbation is introduced in the system. Due to this perturbation, the power of the module alters. If the power enhances due to the perturbation, then the perturbation is carried on in that direction. After the maximum power is accomplished, the power at the next instant decrements and hence the perturbation reverses.

Among different maximum power point tracking algorithms, the perturb and observe algorithm is elementary and also gives desirable results. This algorithm is chosen and certain changes are made in the current work. The flow chart of the method is shown in the fig 20. The algorithm takes the values of current and voltage from the solar photovoltaic module. Power is computed from the assessed voltage and current. The values of voltage and power at k^{th} instant are put in. Then next values at $(k+1)^{th}$ instant are measured again and power is calculated from the measured values. The power and voltage at $(k+1)^{th}$ instant are subtracted with the values from previous instant. If we detect the power voltage curve of the solar photovoltaic module we see that in the right hand side curve where the voltage is almost constant the slope of power voltage is negative ($dP/dV<0$) where as in the left hand side the slope is positive and $dP/dV>0$. The right side curve is for the lower duty cycle (nearer to zero) whereas the left side curve is for the higher duty cycle (nearer to unity). Depending on the sign of dP(P(k+1) - P(k)) and dV(V(k+1) -V(k)) after subtraction the algorithm decide whether to increase the duty cycle or to reduce the duty cycle. The algorithm is elementary and has only one loop [11].

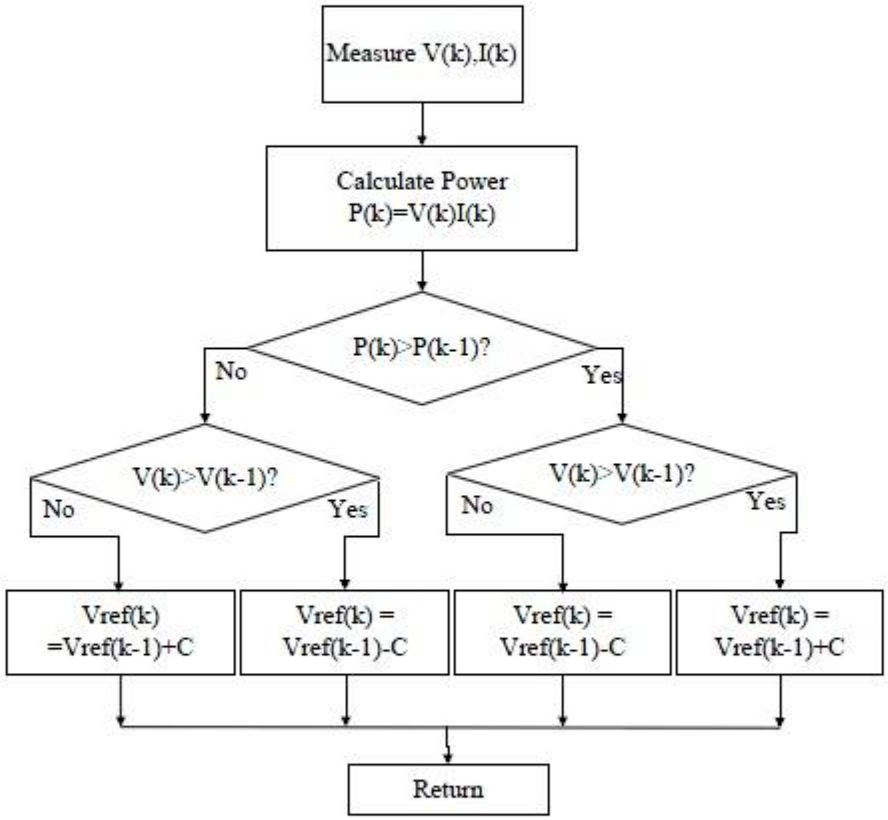

Fig 20: Flow Chart of P&O Algorithm

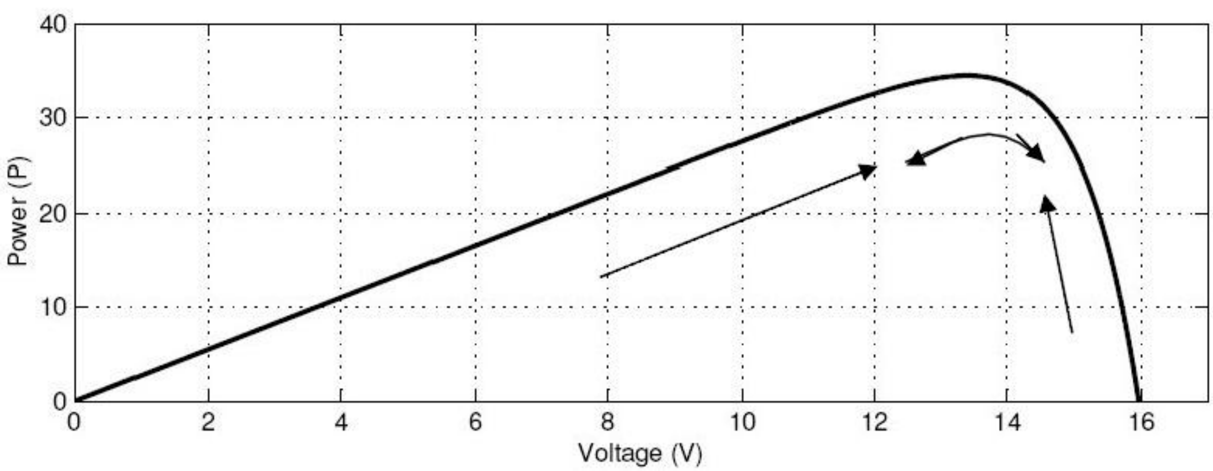

Fig 21: Perturb and observe algorithm

Restrictions of Perturb & Observe algorithm

In a situation where the irradiation changes quickly, the Maximum Power Point also moves on the right hand side of the curve. The algorithm takes it as a change due to perturbation and in the next iteration it changes the direction of perturbation and hence goes away from the MPP as shown in the figure. However, in this algorithm we use only a single sensor, the voltage sensor, to sense the solar array voltage and so the cost of implementation is less and hence easy to carry out. The time complexness of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing in both the directions. When this happens the algorithm has reached very close to the MPP and we can set an appropriate error.

INCREMENTAL CONDUCTANCE METHOD :

Incremental conductance method uses two voltage and current sensors to sense the output voltage and current of the PV array. At MPP the slope of the PV curve is 0.

(dP/dV)MPP=d(VI)/Dv

0=I+VdI/dVMPP

dI/dVMPP = - I/V

The left hand side is the instantaneous conductance of the solar panel. When this instantaneous conductance equals the conductance of the solar then MPP is reached.

Here we are sensing both the voltage and current simultaneously. Hence the error due to change in irradiance is eradicated. Nevertheless, the complexity and the cost of implementation increases. As we go down the list of algorithms the complexity and the cost of implementation goes on increasing which may be suitable for a highly elaborated system. That is why the reason that Perturb and Observe and Incremental Conductance method are the most widely used algorithms. Owing to its simplicity of implementation we have chosen the Perturb & Observe algorithm for our study among the two.

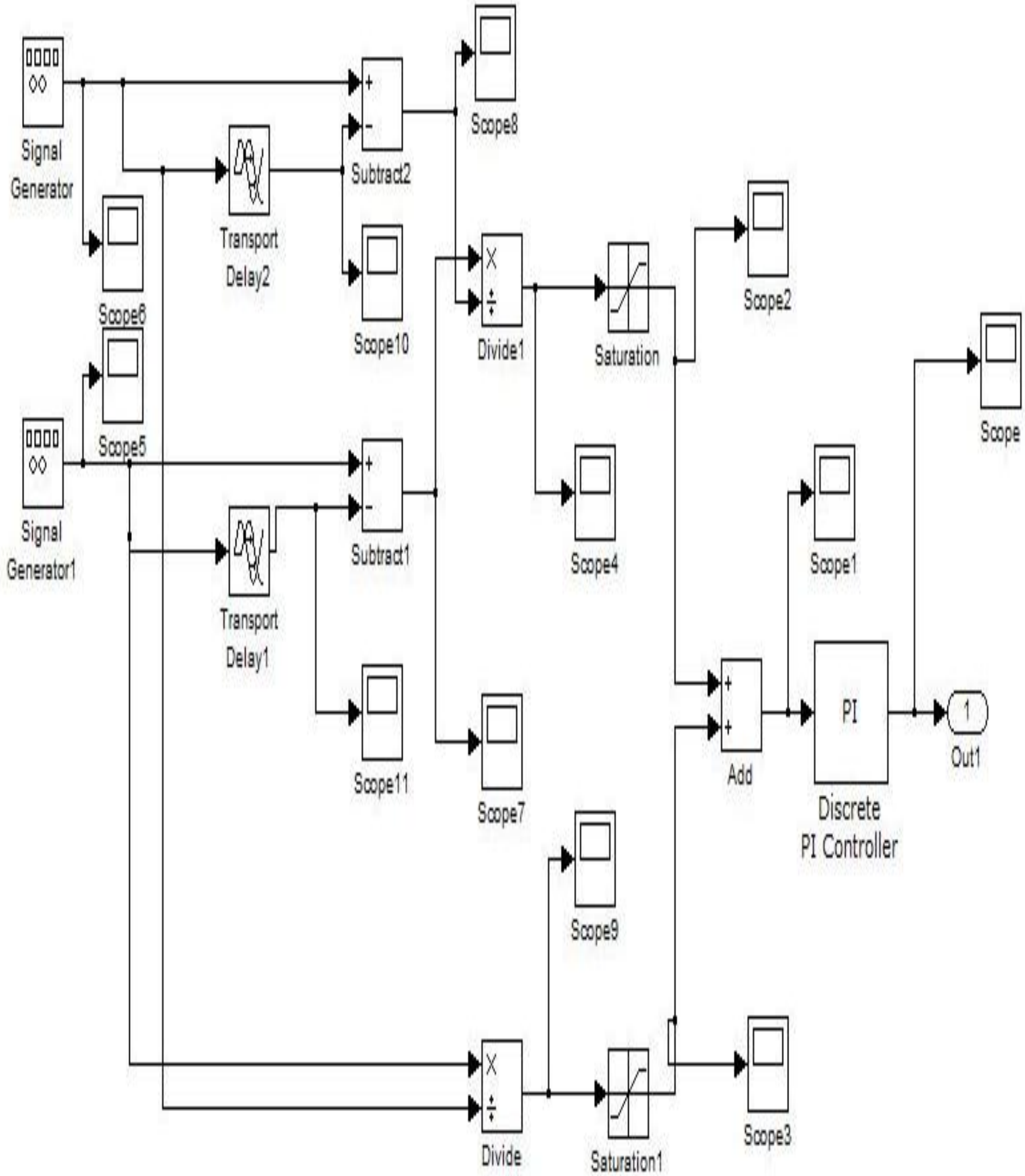

Fig 22: SIMULINK Model for MPPT by Incremental Conductance Method

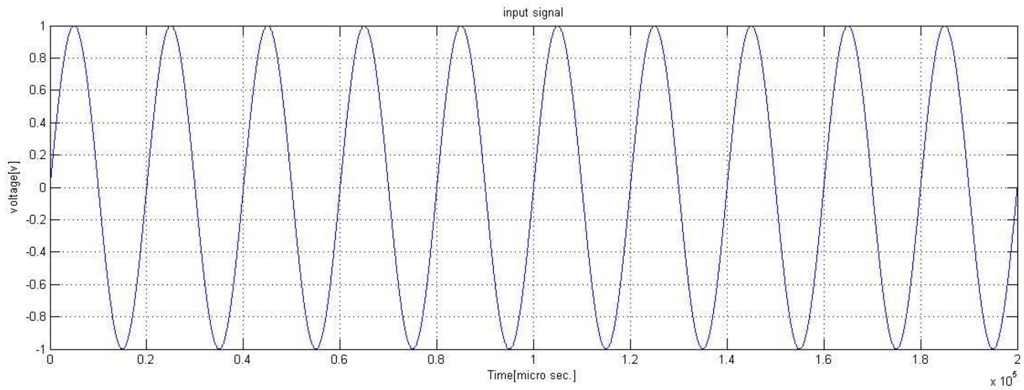

Fig 23: input voltage signal

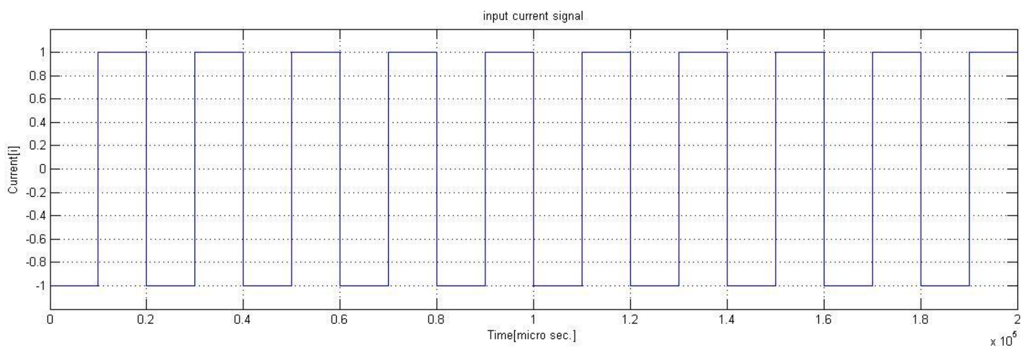

Fig 24: input current signal

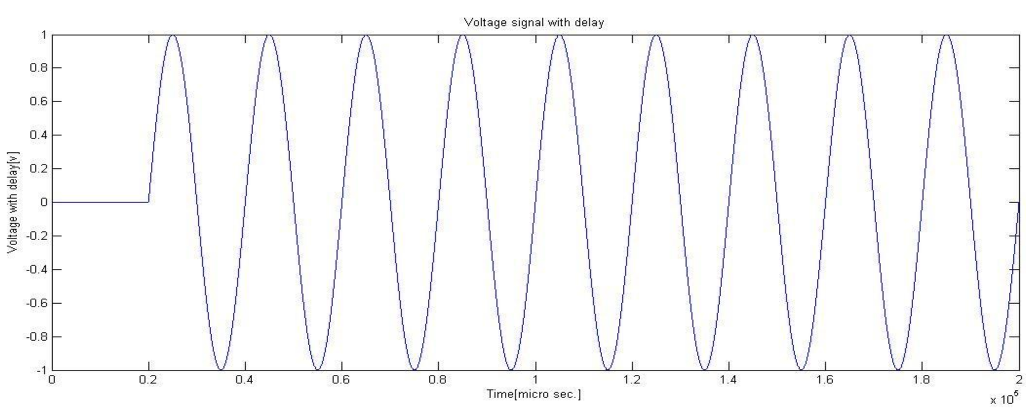

Fig 25: voltage signal with a period of time delay

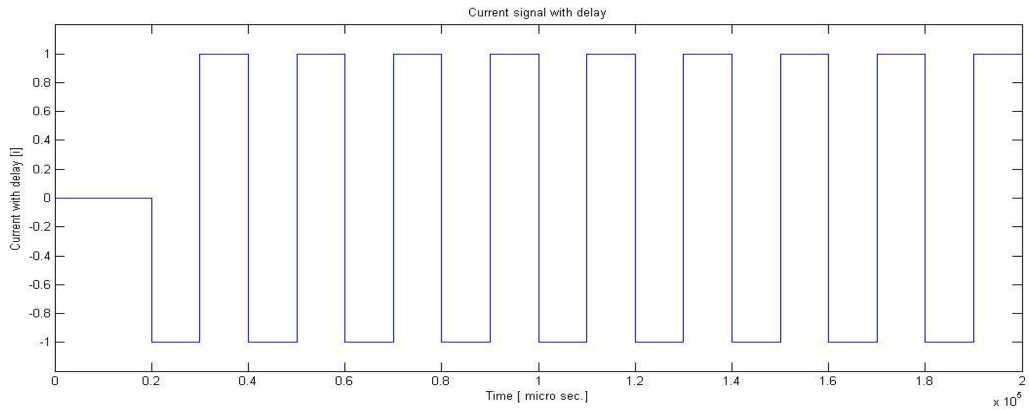

Fig 26: current signal with a period of time delay

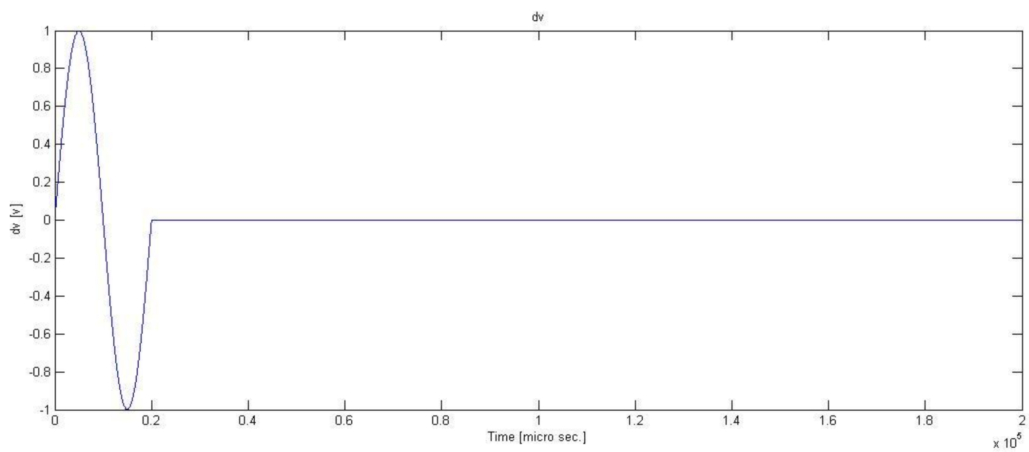

Fig 27: voltage signal deducted by voltage signal with delay (dv)

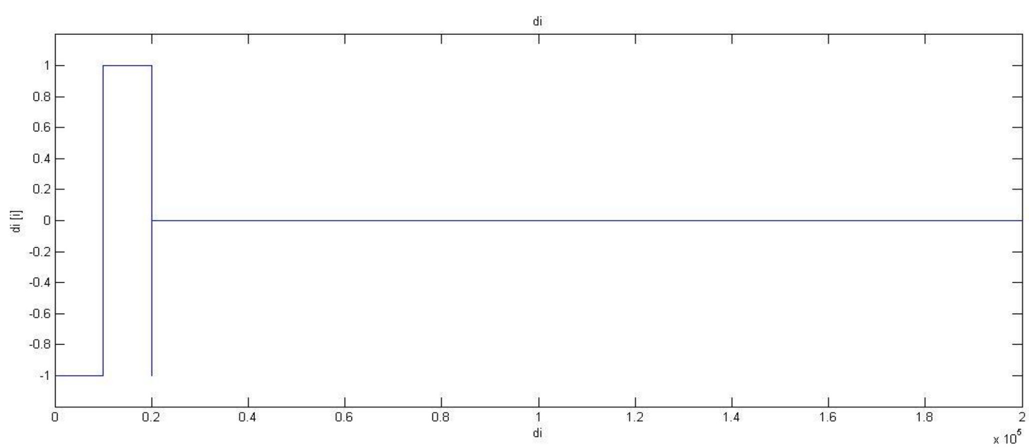

Fig 28: current signal subtracted by current signal with delay

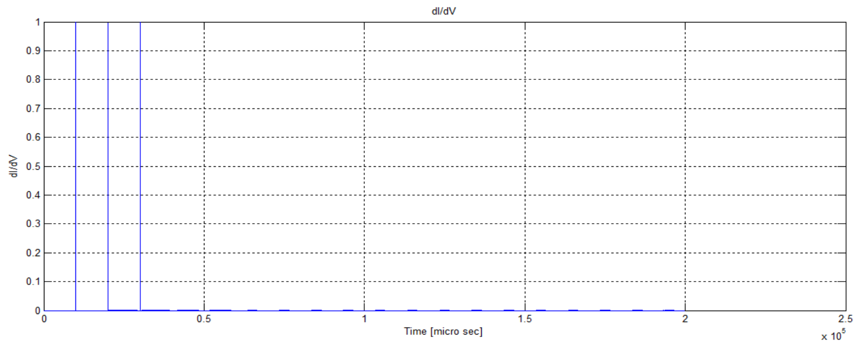

Fig 29: di/dv

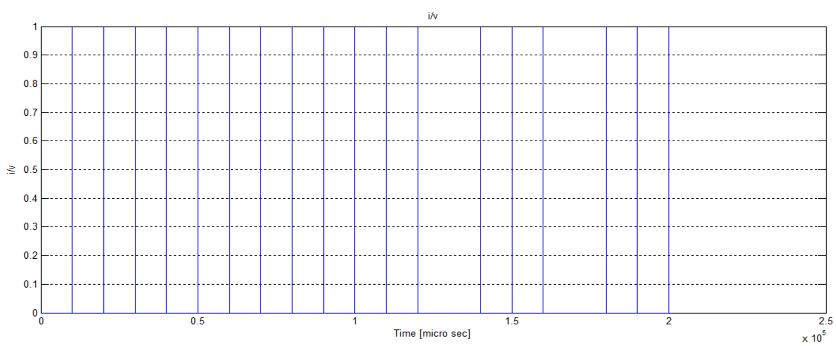

Fig 30: i/v

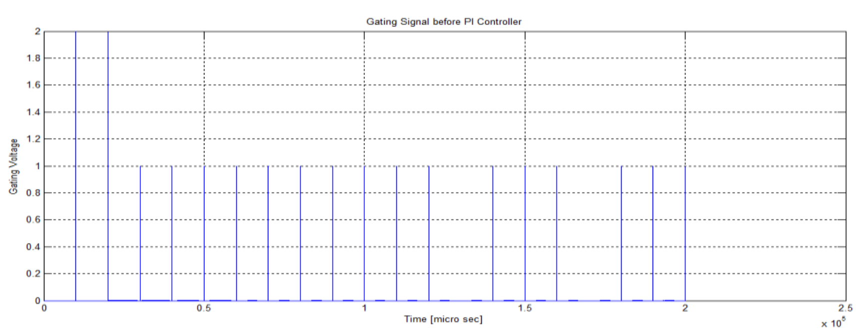

Fig 31: Gating voltage before pi controller

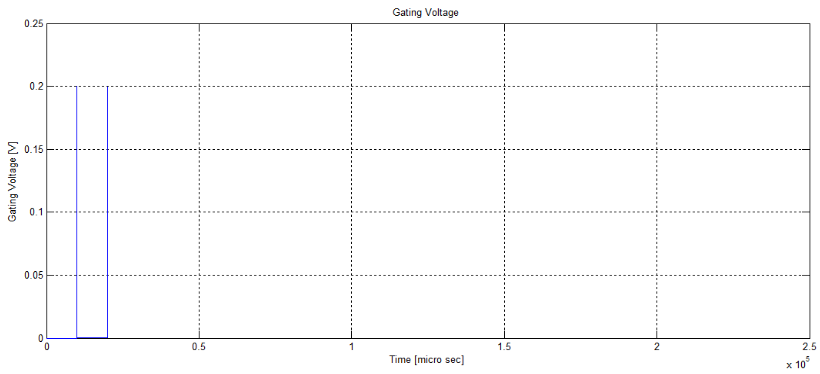

Fig 32: gating voltage after pi controller

CHAPTER 7

CONCLUSION

The open circuit P-V, P-I, I-V curves we obtained from the simulation of the PV array designed in MATLAB environment explains in detail its dependence on the irradiation levels. The entire energy conversion system has been designed in MATLB-SIMULINK environment. Open loop and Closed loop boost converter circuits have been simulated using SIMULINK. The outputs obtained from Incremental Conductance method were found to eliminate the limitations of Perturb & Observe Method.

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